PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : C21D 10/00, 7/06, C22F 3/00	A1	(11) International Publication Number: WO 95/25821 (43) International Publication Date: 28 September 1995 (28.09.95)

(21) International Application Number: PCT/US95/03532

(22) International Filing Date: 21 March 1995 (21.03.95)

(30) Priority Data:
215,553 22 March 1994 (22.03.94) US

(71) Applicant: BATTELLE MEMORIAL INSTITUTE [US/US]; 505 King Avenue, Columbus, OH 43201-2693 (US).

(72) Inventors: DULANEY, Jeff, L.; 5595 Caplestone Lane, Dublin, OH 43017 (US). CLAUER, Allan, H.; 117 Larrimer Avenue, Worthington, OH 43085 (US). TOLLER, Steven, M.; 3308 Pebble Beach Road West, Grove City, OH 43123 (US).

(74) Agents: GOLDSTEIN, Steven, J. et al.; Frost & Jacobs, 2500 PNC Center, 201 East Fifth Street, Cincinnati, OH 45202 (US).

(81) Designated States: CA, JP, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: REDUCING EDGE EFFECTS OF LASER SHOCK PEENING

(57) Abstract

Laser shock peening/processing (LSP) has been used to strengthen fatigue-critical areas in metal parts. Notwithstanding the advantages, one negative effect of LSP occurs at the boundary of the LSP-treated area. In LSP, the laser pulse induces a compressive stress in the material in the area on the surface (and to some extent in the subsurface) of the laser spot. Because the net residual stress in the material must be zero, compensating tensile residual stresses can be created in a boundary region surrounding the laser spot. This region of tensile stress at the surface of the part may be the site of further failure in the specimen if it is not reduced to an acceptable level. The tensile stresses may be reduced by further laser shocking the specimem surface in the boundary region with lower-energy pulses. Since lower energy fluence generally gives lower compensating tensile stress, this secondary LSP essentially reduces or eleminates the tensile compensating region caused by the primary laser shocking and replaces it with a lower compensating tensile region associated with the secondary shocked region further out from the fatigue-critical area.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria	GB	United Kingdom	MR	Mauritania
AU	Australia	GE	Georgia	MW	Malawi
BB	Barbados	GN	Guinea	NE	Niger
BE	Belgium	GR	Greece	NL	Netherlands
BF	Burkina Faso	HU	Hungary	NO	Norway
BG	Bulgaria	IE	Ireland	NZ	New Zealand
BJ	Benin	IT	Italy	PL	Poland
BR	Brazil	JP	Japan	PT	Portugal
BY	Belarus	KE	Kenya	RO	Romania
CA	Canada	KG	Kyrgystan	RU	Russian Federation
CF	Central African Republic	KP	Democratic People's Republic of Korea	SD	Sudan
CG	Congo	KR	Republic of Korea	SE	Sweden
CH	Switzerland	KZ	Kazakhstan	SI	Slovenia
CI	Côte d'Ivoire	LI	Liechtenstein	SK	Slovakia
CM	Cameroon	LK	Sri Lanka	SN	Senegal
CN	China	LU	Luxembourg	TD	Chad
CS	Czechoslovakia	LV	Latvia	TG	Togo
CZ	Czech Republic	MC	Monaco	TJ	Tajikistan
DE	Germany	MD	Republic of Moldova	TT	Trinidad and Tobago
DK	Denmark	MG	Madagascar	UA	Ukraine
ES	Spain	ML	Mali	US	United States of America
FI	Finland	MN	Mongolia	UZ	Uzbekistan
FR	France			VN	Viet Nam
GA	Gabon				

REDUCING EDGE EFFECTS OF LASER SHOCK PEENING

Field of the Invention

This invention relates to improvements in the laser shock processing/peening (LSP) method for increasing the properties, such as hardness, strength, fatigue life (or fatigue strength), and corrosion resistance of metallic materials or of welds between metal surfaces. The LSP method was originally disclosed in U.S. Patent No. 3,850,689 as an improvement on existing mechanical peening processes for improving hardness in treated materials.

The interaction of a pulsed laser beam with the surface of a material gives rise to a pressure pulse (shock wave) that propagates into the material and changes its properties. In the case of metals, for example, the changes in properties are caused by the introduction of cold work that increases the hardness and strength of the material. By appropriate tailoring of the peak pressure and width of the shock wave, it is possible to enhance selected material properties, such as fatigue strength, and at the same time not adversely affect other properties, such as corrosion resistance. It is possible also to shock process a finished workpiece of material without significantly disturbing its surface, where a thin sacrificial layer of overlay material has been attached intimately onto the surface of the workpiece.

Shock processing with coherent radiation has several advantages over what has been done before. For example: (a) The source of the radiation is highly controllable and reproducible. (b) The radiation is easily focused on preselected surface areas and the operating mode is easily changed. This allows flexibility in the desired shocking pressure and careful control over the workpiece area to be shocked. (c) Workpieces immersed in hostile environments such as high temperature and high vacuum can be shock processed. (d) It is easy to shock the workpiece repetitively. This is desirable where it is possible to enhance material

properties in a stepwise fashion. Shocking the workpiece several times at low pressures can avoid gross deformation and spallation of the workpiece. (e) The process is readily amenable to automation. (f) Nonplanar workpieces can be shock processed without the need of elaborate and costly shock focusing schemes.

Notwithstanding these advantages, one negative effect of LSP occurs at the boundary of the LSP-treated area, especially in softer materials. In LSP, the laser pulse induces a residual compressive stress in the material in the area on the surface (and to some extent in the subsurface) exposed to the laser spot. The negative effect is then produced at the boundary of the processed area and slightly beyond, in the form of a compensating residual tensile stress in the material. This region of tensile stress may be the site of failure in the specimen if this residual tensile stress is not reduced to an acceptable level.

Summary of the Invention

It is an object of the invention to provide a process to suppress or eliminate the surface residual tensile stress which is induced in the boundary region of a laser-shock-processed area.

In accordance with the objective, the invention is a method of improving material properties of a solid material by laser shock processing. Typically, one or more laser pulses having an average energy fluence of at least about 10 J/cm^2 and a rise time of not longer than about 5 nanoseconds are directed to the surface of the material to provide shock waves in the material. The invention comprises laser shocking the solid material in a primary shock region of the surface of the material to induce compressive residual stress in the primary shock region and compensating tensile residual stress in the material surface in the boundary area adjacent the primary shock region, and then laser shocking the material in a secondary shock region, including at least a portion of the compensating tensile residual stress area of the material surface adjacent the primary shock region, with at least one secondary pulse of coherent laser radiation having an average energy fluence lower than the average energy fluence of the primary laser pulse(s). This secondary shocking results in a reduction of the compensating tensile residual stress in the (secondary) shocked area. The words

primary and secondary are not intended to mean that the primary one must occur first in time. The primary or the secondary pulse may be applied in either order to gain the benefits of the invention.

In another embodiment of the invention, instead of a using a secondary laser shock, the secondary shock region may be conventionally shot peened with a barrage of hard particles or shot to reduce the compensating tensile residual stress.

It is preferred to select the frequency, fluence and location of the secondary laser pulse(s) or the velocity, size and duration of the shot such that the compensating tensile residual stress is reduced to below the baseline surface residual stress. And it is further preferred that the entire area of the higher compensating tensile residual stress be treated with the secondary peening so that no areas of high surface residual tensile stress exist as a result of the primary shocking.

Because the secondary peening can cause its own area of compensating tensile stress in its boundary area outside of the secondary shock region, the invention further includes the possibility of shock peening a tertiary shock region. With laser peening, the invention comprises using at least one tertiary laser pulse having average energy fluence lower than the average energy fluence of the secondary laser pulse(s) and directing it to the boundary area of the surface of the material adjacent the secondary shock region (outside the secondary shock region on the opposite side from the primary shock region). With mechanical peening, the invention comprises directing to the tertiary shock region, a multiplicity of solid spheres such that the compensating tensile residual stress from the secondary peening is reduced.

The secondary laser pulse(s) may conveniently be of the same shape as the primary pulse(s), be concentric with the primary pulse(s) and overlap partially or completely with the primary pulse(s), but they need not. Conveniently, the primary pulse and the secondary pulse may be circular in shape and concentric, and the secondary pulse may be of larger diameter than the primary pulse and completely overlap it. The tertiary pulse(s) may conveniently follow the same guidelines with respect to the secondary pulse(s).

The secondary (and/or tertiary) pulse(s) may have a spatial energy distribution which is symmetric or asymmetric. The asymmetric distribution may be particularly useful if it is selected such that the energy gradually reduces as the distance from the primary shock region increases. A series of separate spots around the circumference of the primary shock region is also useful.

Preliminary results indicate that the present process can be useful with non-metals such as ceramics and polymers as well as with metals. The development of the laser-induced stress wave and use of the overlays can be approximately the same irrespective of the target material. The stress wave can pass into the target material and modify its properties whether it is metallic or non-metallic.

Description of the Drawings

FIGURE 1 is a schematic of a representative laser system which can be used for shocking specimens according to the invention.

FIGURE 2 shows the step down or feathering of laser beam spots for secondary laser shocking which reduces the undesirable tensile stress according to the invention.

FIGURE 3 shows representations of several different configurations of laser beam spots used for secondary laser shocking to reduce tensile stress at the periphery of primary laser shocked regions according to the invention.

FIGURE 4 shows examples of several different spacial energy distributions for secondary laser shocking according to the invention.

FIGURES 5A and 5B show the surface residual stress profiles of laser shocked specimens before and after the secondary laser shock treatment according to the invention.

FIGURES 6A and 6B show the surface residual stress profiles of second laser shocked specimens before and after the secondary laser shock treatment according to the invention.

Description of the Preferred Embodiments

When metal parts are fabricated, forming processes and surface treatments (machining, grinding, polishing, etc.) produce a (baseline) residual stress, which is often slightly tensile and on the surface (to some extent also the subsurface). When fatigue-critical zones are strengthened by laser shocking, a compressive stress is induced in the shocked region (or primary shocked region, PSR). A compensating tensile stress in the material is then induced at the edge or boundary of the PSR which is additive with the baseline residual stress which can result in a highly tensile region around the PSR. (Of course, if the specimen surface has been prestressed so that the baseline residual stress is compressive, then the LSP-induced tensile stress would have the effect of reducing the compressive stress at the boundary.)

The Laser Shock Process and Apparatus

The LSP process typically includes applying an opaque, absorbing coating and a transparent overlay to a workpiece and directing a laser pulse (or a plurality of pulses) on the overlay. Most of the energy from the laser pulse passes through the transparent overlay and vaporizes a portion of the absorbing coating. For sufficiently short pulses and sufficiently intense beams, the vapor forms a plasma with very high peak pressure. The transparent overlay serves as a tamp and confines the plasma to enhance the magnitude and duration of the pressure pulse that it exerts on the surface of the workpiece. A shock wave is generated by the pressure pulse. It travels into the material and, in the case of metals, alters the microstructure in such a way as to leave a residual compressive stress in the workpiece. The residual stress results in greatly improved fatigue properties for the treated region.

Typically, the pulses of coherent radiation have an average energy fluence of at least about 10 Joules per square centimeter. It is preferred that the rise time of the radiation pulse is not longer than about 5 nanoseconds. For production processes it is also preferred that the pulse rate is fairly rapid.

Referring now to Figure 1, typical known apparatus 10 is shown, suitable for improving properties of a metallic material in a target 11 by providing

shock waves therein. Additional details of the apparatus can be found in U.S. Patent 5,131,957 which is incorporated herein by reference. The apparatus shown in Figure 1 may produce a plurality of pulses of coherent radiation 12 having average energy fluence of at least about 10 Joules per square centimeter and rise time of not longer than about 5 nanoseconds within a fluorescence envelope lasting about 0.5 to 5 milliseconds.

The coherent radiation 12 is generated by an oscillator 13-17 comprising a rear mirror 13, a laser pump cavity 14, a polarizer 15, a pockels cell 16, and an output coupler 17. The laser pump cavity 14 comprises a gain medium, such as a neodymium-glass laser rod, pumped by flashlamps that are driven at regular intervals of about 0.5 to 10 seconds by a pulse forming network (PFN). One such laser pump cavity 14 that has been used conveniently in the apparatus 10 comprises the following components (along with examples of specific models) manufactured by Kigre, Inc. of Hilton Head, South Carolina:

Laser Cavity, 150 mm arc length (eg. FC-500/2 by Kigre, Inc.)

Laser rod, 10 mm diameter by 20 cm long (eg. Schott Glass Technology LG760)

Two Fluid-cooled Flashlamps (eg. as shown in US Patent 5,127,019)

Controller (eg. Model 883 with integral 330 watt Power Supply by Kigre, Inc.)

Closed Cycle Cooling System (eg. by Kigre, Inc.)

The oscillator 13-17 provides an approximately rectangular fluorescence envelope lasting about 0.2 to 5 milliseconds. The coherent radiation 12 from the laser pump cavity 14 is linearly polarized. The polarizer 15 breaks the radiation 12 down into two linearly polarized orthogonal components; one of which (component B) it reflects away as indicated at 12B; and the other (component A) it transmits on, as indicated at 12A, to the pockels cell 16.

With a proper potential present across it (about 3,300 volts for a cell of transverse deuterated potassium dihydrogen phosphate), the pockels cell 16 retards

the coherent radiation 12A one-fourth wavelength (90 degrees) while transmitting it on to the output coupler 17, which reflects about one-half of it back toward the polarizer 15. The reflected energy proceeds back through the pockels cell 16 with a further retardation of one-fourth wavelength (90 degrees). So the back radiation is one-half wavelength (180 degrees) out of phase with the forward radiation of component A, thus having the opposite polarization (B), and it is reflected away by the polarizer 15, as indicated at 12C, so as not to return to the laser pump cavity 14. Thus, laser energy builds up and is stored in the laser rod of the pump cavity 14, because oscillations cannot occur.

After at least about 100 microseconds, the potential across the pockels cell 16 is reduced to zero, typically by shorting it to ground, for about 1 to 5 microseconds producing a laser pulse.

The output coupler 17 comprises a partially reflective mirror that transmits about half of the energy. It is generally preferred to provide a radiation pulse with a short rise time, in which case each pulse 12 is passed through a pulse sharpener. One such pulse sharpener 18 comprises a coating of aluminum about 150 to 5,000 angstroms thick on a supporting film that is substantially transparent and thin enough to be non-distorting to the radiation wavefront. The supporting film typically comprises a strong polyester material such as oriented, at least partially crystalline, polyethylene terephthalate, about 1 to 40 micrometers thick. One such material is Mylar, a product of E.I. du Pont de Nemours & Company. Mylar is birefringent, and its optical axis should be oriented to correspond with the polarization of the polarizer 15.

The radiation pulse 12 strikes the aluminum film 18, typically vaporizing an area of about 0.1 to 0.2 square millimeters of the film in about 0.1 to 3 nanoseconds, after which the area of vaporization typically expands to about 1 to 1,000 square millimeters in about 2 to 10 nanoseconds. This sharpens the leading edge of the radiation pulse 12 passing through the hole where the film 18 has been vaporized away, and the modified pulse 12 is directed to a preamplifier 20. Where necessary or convenient, planar mirrors 19 may be included in the path of the radiation 12 to change or adjust the direction of the beam of radiation 12.

The preamplifier 20, which may be (and typically is) similar to the laser pump cavity 14, amplifies the radiation pulse 12, typically by about 3 to 10 decibels, and the amplified radiation 12 proceeds by way of a telescope, typically comprising a negative lens 21 and a positive lens 22, to an amplifier 23, which typically further amplifies the radiation pulse 12 by about 5 to 15 decibels. One amplifier 23 that has been used conveniently in the apparatus 10 comprises the following components by Kigre, Inc. of Hilton Head, South Carolina (except the laser rod):

Power Amplifier Assembly, FA-1000/2

28 mm dia. x 810 mm long Schott APG-1 Laser Rod of strengthened phosphate glass

Two Fluid-cooled Lamps, 63 cm arc length

Model 886-2 Power Supply compatible with 883 Controller

Dual PFN assemblies

Coolant-to-water Cooling System

The amplified radiation pulse 12 is focused by a positive lens 24 onto a desired area of the surface 25 of the target 11, to provide an average energy fluence therein typically of at least about 10 (and preferably about 10 to 500) Joules per square centimeter, and an average power flux on the target of at least about 10^7 (and preferably about 10^9 to 10^{11}) watts per square centimeter, with pulse lengths typically of about 10 to 1,000 nanoseconds. The maximum power flux will be limited by the formation of a reflecting plasma at the target surface. This maximum power flux will increase as the laser wavelength decreases. For example for a laser wavelength of 0.53 micrometer the maximum power flux will be approximately four times that for a wavelength of 1.06 micrometers.

A portion of the output 12 of the amplifier 23, typically about 10 percent, may be directed by a beam splitter 37 and mirror 39 to a second similar amplifier 23' to provide a second amplified radiation pulse 12', focused by a positive lens 24' onto a desired area of the surface 25 of the target 11

simultaneously with the pulse 12 from the amplifier 23. A portion of the output 12' from the amplifier 23' may be directed by a beam splitter 37' to an additional amplifier, and so on, to provide additional pulses to the target 11. Typically pulses from the different amplifiers are directed to the same area on the surface 25 of the target 11, to overlapping areas on the surface of the target 11, and/or to areas that are on opposite surfaces of the target 11.

The portion of the apparatus 10 already described above provides one properly sharpened pulse within each fluorescence envelope in the same manner as is described above. Two radiation pulses within each fluorescence envelope can be provided by incorporating a second oscillator by utilizing the other radiation component 12B from the laser pump cavity 14 and the polarizer 15 and directing the component through a second pockels cell and output coupler. The pulse can also be directed through a second pulse sharpener and then reflected from a second polarizer (to join the 12A pulse passed through the second polarizer) before being directed to the preamplifier 20 by the mirrors 19 with the 12A pulse.

Typically a layer 26 of solid or liquid overlay material is attached to a surface 25 of the target 11, and the radiation pulse 12 is directed to the layer 26 of overlay material. The thickness of the target 11 plus any overlay 26 that is absorbent to the radiation 12 preferably is at least about two micrometers greater than the mean free path of the radiation 12 therein. The target 11 preferably is mounted against a substantially larger solid support member 31 or is rigidly held by a fixture, either of which is rigidly attached to a table or other large fixed object.

These overlay materials may be of two types, one transparent to the laser radiation and one opaque to the laser radiation. They may be used either alone or in combination with each other; but it is preferred that they be used in combination, with the overlay 26 directly on the surface 25 of the target 11 being opaque and the outer overlay 30 or 27 being transparent.

The layer of overlay material 26 should be attached securely over the surface 25 of the target 11 so as to be in intimate surface contact throughout the area to be radiated. Where some or all of the overlay material comprises a liquid, as at 27, it may be held within an enclosure 28, of which at least the front portion

29 preferably is transparent to the radiation 12, or it may flow over the area to be treated without restriction by an enclosure. Where a liquid transparent overlay 27 is used, the solid transparent overlay 30 may be omitted, if desired. Where only the solid transparent overlay 30 is desired, the liquid 27 and the enclosure 28 may be omitted.

In order to keep from having to move the pulse sharpener very quickly, a second pulse sharpener can be added to the apparatus. A second oscillator can be utilized comprising existing laser pump cavity 14 and polarizer 15 and adding a second pockels cell and output coupler by means of which the other radiation component 12B may be used to provide a second sharpened pulse by way of a second pulse sharpener, mirror and polarizer, thereby reflecting the component B radiation to the first mirror 19; and from there the path of the radiation 12 is the same as that of the component 12A. Typically the second pockels cell is shorted about 150 microseconds later than is the first pockels cell 16, so that the second radiation pulse 12 will strike the target 11 about 150 microseconds after the first pulse 12. Thus the modified apparatus may provide two radiation pulses to the target for each fluorescent envelope and the films in the pulse sharpeners need to move only about 1 centimeter per second.

Mechanical Shot Peening

Mechanical shot peening is a process that has been practiced for many years to work harden the surface of metal parts. Typically, a metal part is placed in an enclosed area and is bombarded by multiplicity of solid, often spherical objects. These are typically steel shot. The impact of the shot work hardens the surface (leaving a residual compressive stress) over the impact area. The degree of residual stress is affected by the weight and size of the shot, the velocity and number of impacts, and hardness of the shot, among other process conditions well know in the art. Mechanical shot peening may be used where the surface condition of the part is not critical, because the impacts also leave impressions in the surface, and where the shape is not complex since the balls have to have a line of flight access to the peened area. Portions of the part may be selectively treated by using a rubber masking over areas not to be peened.

LSP Edge Effects

The beneficial result of LSP is a compressive residual stress that covers the same area (or slightly more) as the laser pulse (also known as the laser spot or shot). Because the net residual stress in the bulk material must be zero, compensating tensile residual stresses are also present, and they do appear in a boundary region adjacent to and surrounding the laser spot. This region may have high surface tensile stresses, as shown in Figure 5. Higher laser beam fluence generally gives rise to higher compressive stress and potentially higher compensating tensile stress.

Figure 5A shows typical residual (surface) stress profiles for a titanium alloy specimen laser shocked three times with a 200 J/cm^2 circular beam. Residual stress measurements (ordinate) were taken at the surface of the specimen at radial locations measured from the center of the primary shock region (abscissa). The edge of the PSR is shown as the vertical dashed line at about 2.5 mm. The dashed curve represents the residual stress at the testing location in the radial direction to the (circular) PSR and the solid curve represents the residual stress at the testing location in the tangential direction. The background or baseline residual stresses (in the untreated material) in the tangential direction and the radial direction are shown by the horizontal dashed lines at about 360 and 185 MPa, respectively. As can be seen, the residual stress in the PSR is compressive, but turns tensile just outside the PSR and ultimately exceeds the background residual stress at some distance from the PSR. This tensile area can be a source for fatigue failure in commercial parts. The highest magnitude of the residual stress is generally on or just below the surface of the material, but subsurface residual stresses are also present and respond similarly to the LSP treatments.

We have found that the tensile stresses may be reduced by further laser shocking the specimen with lower-energy pulses in the compensating tensile residual stress area adjacent the PSR. Since lower energy fluence generally gives lower compensating tensile stress, this secondary LSP significantly reduces or eliminates the area of compensating tensile residual stress caused by the primary laser shocking and in turn creates a lower compensating tensile residual stress region associated with the secondary shock region farther out from the PSR (and

farther from the fatigue critical area). So the secondary shocking reduces or eliminates the compensating (primary) tensile residual stress area, and can result in a lower compensating (secondary) tensile residual stress area more remote from the fatigue critical area which, of course, would typically lower the risk of failure. We have found that the primary or the secondary pulse may be applied in either order (that is, the secondary pulse may actually be applied first) to gain the benefits of the invention.

Alternatively to the laser peening, the compensating tensile residual stress may be reduced in the secondary shock region by conventional mechanical shot peening. Shot peening is carried out on the secondary region to such an extent that the compensating tensile stress is reduced to near the background level or is nearly eliminated completely.

This secondary peening treatment, also known as fade out or feathering, is shown schematically in Figure 2 wherein a fatigue critical zone X exists in a specimen 40. The specimen is laser-shock processed, with a primary spot of 200 J/cm^2, for example, as represented by element 41 over a primary shock region (the height being indicative of fluence level), resulting in a compensating tensile stress in the material in the boundary area outside of and adjacent the PSR. To reduce or eliminate such tensile stress outside the PSR, a second laser shock is provided by annular spot of 150 J/cm^2, for example, as represented by element 42 overlapping the periphery of the PSR, and resulting in a reduction or elimination of the (primary) compensating tensile stress in the area of secondary shocking 42.

The secondary laser shocking can also result in a compensating tensile stress of its own in the material in the boundary area outside of and adjacent to the secondary shocked region. Therefore, a third laser shock may optionally be provided by an annular pulse of 75 J/cm^2, for example, as represented by element 43 overlapping the periphery of the second laser pulse(s) and resulting in an even further reduction or elimination of the (secondary) compensating tensile stress in the area of tertiary shocking 43 and an even lower (tertiary) compensating tensile stress in the material outside of and adjacent to the tertiary shock region, and so on until an acceptable level of residual tensile stress is achieved. Once again, the primary, secondary and tertiary pulses may be applied in any order.

The secondary pulse shape (the cross-sectional beam geometry on the specimen) need not be coincident with the primary pulse. For example, the primary spot 50 may be circular and the secondary pulse 51 either circular (Figure 3A), overlapping the entire primary pulse, or annular (Figure 3B), overlapping only the outside edge. A plurality of smaller pulses 52 may also be used to shock the area outside the PSR, such as shown in Figure 3C. The secondary pulse can also be of a different shape than the primary pulse and need not be concentric or symmetric. Of course, the same applies to the tertiary pulse with respect to the secondary pulse.

An alternative method of fade out or feathering which is particularly desirable involves the modification of the spatial distribution of the laser beam to yield a secondary laser pulse which is not uniform in intensity across the shock region. This means that instead of discrete steps in intensity (such as shown in Figure 2), the secondary (and/or tertiary) pulses can have an intensity profile which decreases gradually at increasing distance from the PSR (ie. the higher fluence region is nearer the PSR). Some sample beam intensity profiles are shown in Figure 4 wherein the intensity is in the vertical dimension and profiles are each shown across a secondary (or tertiary) shock region on the material surface: A. Flat Top, B. Symmetric, C. Symmetric, D. Symmetric, E. Gaussian, F. Asymmetric, G. Asymmetric. Many lasers produce a Gaussian or near-Gaussian spatial distribution. Special optics (perhaps binary optics) could be fabricated to generate other spatial distributions.

Ways of Providing the Second Pulse

The secondary pulses can be provided in the same manner as above described for the PSR and by the same laser or by a different laser at a later time. The secondary pulses can be provided substantially after the primary pulses or can be nearly coincident in time. One way of making them nearly coincident involves the use of a second smaller amplifier 23' (Figure 1) to provide a second, lower-energy, amplified radiation pulse 12', focused by a positive lens 24' onto the desired expanded area of the surface 25 of the target 11 simultaneously with or just after the higher-energy pulse 12 from the amplifier 23. In the same way, a portion

of the output 12' from the amplifier 23' may be directed by a beam splitter 37' etc, and any convenient number of amplifiers may be employed similarly to provide additional lower-energy pulses to the target 11. These lower-energy pulses from the different amplifiers would be directed to the areas at the boundary of the primary spot on the surface 25 of the target 11.

EXAMPLES

In each of the following examples, unless otherwise indicated, laser shock hardening of a material according to the present invention was performed as described below, using apparatus as shown in Figure 1, both for the primary shocking and the secondary feathering at the edge of the primary shocked region (PSR). The principal components were a Kigre oscillator 14 and preamplifier 20, as described above, and two beam amplifiers 23 which were similar to the Kigre amplifiers but which had flashlamps located more uniformly around the rod so that the spatial amplitude of the radiation was more uniform (such as shown in U.S. Patent 5,127,019, which is incorporated herein by reference). The outputs from the amplifiers 23 were directed to spots at a given location on the target 11. Each primary laser spot was generally circular and approximately 5 millimeters in diameter. The target specimens were about 2.5 cm square and 1.25 cm thick. The target was a titanium alloy containing 6 % aluminum and 4 % vanadium, by weight.

The target surface was coated to absorb the laser energy, and thus avoid any possible melting at the surface. The standard procedure was to spray the surface with black spray enamel in two multi-pass steps. The enamel usually applied was Zynolyte Rustmate 1010 Bar-B-Que black. The Zynolyte paint is sold by Zynolyte Products Company, Carson, California and manufactured by Major Paint Company, Torrance, California. Other dark paints can be used with varying results. It appears useful if the paint is not allowed to dry completely, since this prevents cracking and spalling of the paint layer.

After spraying the paint and drying for about 15 minutes, the sample target was loaded into a holding fixture. Each sample was thick enough that no backup or impedance matching material was necessary to eliminate or minimize

any back reflected shock pulse, which in thinner targets could appreciably reduce the net amount of residual stress stored at the shock surface.

A transparent overlay material was provided over the flat black paint to confine the shock pulse and direct it into the sample. Typically the overlay comprised flowing water, introduced at a convenient location above the area to be hit by the laser beam and adjusted so that it spread out into a substantially flat uniform sheet approximately one millimeter thick as it flowed over the area to be laser shock processed.

Where desired, with a selected spot size, lower energy fluences were obtained by placing attenuating optical filters in the path of the laser beam.

Example 1

Two titanium alloy specimens (Nos. 100 and 101) were laser shocked over a primary shock region as described above with three pulses, each with an energy fluence of 200 J/cm^2. The residual stress of one of the specimens (#100) was measured at several points along a radius of the PSR (in a "vertical" trace). The residual stress profile is shown in Figure 5A. The dashed curve represents the residual stress at each testing location in the (vertical trace) radial direction and the solid curve represents the residual stress at each testing location in the (vertical trace) tangential direction to the PSR. The edge of the PSR is shown as the vertical dashed line at about 2.5 mm. The background residual stresses (in the untreated material) in the tangential direction and the radial direction are shown by the horizontal dashed lines at about 360 and 185 MPa, respectively. As can be seen, the residual stress in the PSR is compressive, but turns tensile just outside the PSR and ultimately exceeds the background residual stress at some distance from the PSR. We believe that most of the residual stress is in the surface of the material and due to surface treatments such as grinding and polishing. Lower subsurface residual stresses were also present.

The second of the two specimens (#101) was again laser shocked with a single, circular 100 J/cm^2 pulse over a spot size of approximately 7 mm with the center shifted by about 0.5 mm with respect to the center of the PSR. The outside edge of this spot is located then at the dashed vertical line shown at the 4 mm mark in Figure 5B. After the secondary feathering, the surface residual stress was measured at several points, both in the radial direction (dashed curve) and the tangential direction (solid curve), along a radius to the PSR. The residual stress profile is shown in Figure 5B. Note that the background residual stresses are slightly different in the specimen #101. However, the important comparison is the residual stress with respect to the background. As can be seen, the surface tensile residual stresses in both directions have been suppressed such that (within the accuracy of the measurements) they do not exceed the background residual stress even at some distance from the PSR.

Example 2

Two titanium alloy specimens (Nos. 100 and 102) were laser shocked over a primary shock region as described in Example 1 above with three, circular, 200 J/cm^2 pulses over a PSR having a radius of about 2.5 mm. One of the specimens (#100) was the same sample as used in Example 1 but the surface residual stresses were measured at several points along a radius of the PSR in a direction perpendicular to the radius measurements taken in Example 1(ie. a "horizontal" trace). The residual stress profile is shown in Figure 6A. The dashed curve represents the residual stress at each testing location in the (horizontal trace) radial direction and the solid curve represents the residual stress at each testing location in the (horizontal trace) tangential direction to the PSR. The edge of the PSR is shown as the vertical dashed line at about 2.5 mm. The background residual stresses (in the untreated material) in the tangential direction and the radial direction are shown by the horizontal dashed lines at about 185 and 360 MPa, respectively (the radius in this example is perpendicular to the radial direction in Example 1). As can be seen, the residual stress in the PSR is compressive, but turns tensile just outside the PSR and ultimately slightly exceeds the background residual stress at some distance from the PSR.

The second sample (#102) was then laser shocked with an overlapping, single, circular 50 J/cm^2 pulse over a spot size of approximately 10 mm with the center shifted by about 1.5 mm with respect to the center of the PSR. The outside edge of this spot is located then at the dashed vertical line shown at the 6.5 mm mark in Figure 6B. After the secondary feathering, the surface residual stress was measured at several points, both in the radial direction (dashed curve) and the tangential direction (solid curve), along a radius to the PSR. Again, the background residual stresses (the horizontal dashed lines) are slightly different in the specimen #102, but the important comparison is the residual stress with respect to the background. As can be seen, the residual stress in both directions have again been suppressed and stretched out such that (within the accuracy of the measurements) they do not exceed the background residual stress even at some distance from the PSR.

We Claim:

1. A method of improving material properties of a solid material by laser shock processing wherein coherent laser radiation having an average energy fluence of at least about 10 J/cm^2 is directed to the surface of the material to provide shock waves therein, comprising

directing to a primary shock region of the surface of the material at least one primary laser pulse having a preselected average energy fluence, and

directing at least one secondary laser pulse having an average energy fluence lower than the preselected average energy fluence of the at least one primary laser pulse to a secondary shock region including at least a portion of the surface of the material adjacent the primary shock region.

2. The method according to claim 1 for improving material properties of a solid material wherein

the secondary shock region overlaps at least a portion of the primary shock region.

3. A method of improving material properties of a solid material by laser shock processing as claimed in claim 1 which further comprises

directing at least one tertiary laser pulse having average energy fluence lower than the average energy fluence of the at least one secondary laser pulse to an area of the surface of the material which is adjacent to the secondary shock region and does not include the primary shock region.

4. The method according to claim 3 for improving material properties of a solid material wherein

the secondary shock region overlaps at least a portion of the primary shock region and the tertiary shock region overlaps at least a portion of the secondary shock region.

5. The method according to claim 4 for improving material properties of a solid material wherein

the secondary shock region overlaps the entire primary shock region and the tertiary shock region overlaps the entire secondary shock region.

6. A method of improving material properties of a solid material by laser shock processing wherein

at least one laser pulse having an average energy fluence of at least about 10 J/cm^2 and a rise time of not longer than about 5 nanoseconds is directed to the surface of the material having a baseline surface residual stress to provide shock waves in the material, comprising

laser shocking the solid material by directing at least one primary laser pulse having a preselected average energy fluence to a primary shock region of a surface of the material thereby inducing compressive residual stress in the primary shock region and compensating tensile residual stress in an area of the material surface adjacent the primary shock region, and

directing to a secondary shock region, including at least a portion of the compensating tensile residual stress area of the material surface adjacent the primary shock region, at least one secondary pulse of coherent laser radiation having an average energy fluence lower than the preselected average energy fluence of the at least one primary laser pulse such that the compensating tensile residual stress is reduced in the area of overlap of the secondary shock region and the compensating tensile residual stress area of the material surface adjacent the primary shock region.

7. The method according to claim 6 for improving material properties of a solid material wherein

the at least one secondary pulse of coherent laser radiation is selected such that the compensating tensile residual stress is reduced to below the baseline surface residual stress in the area of overlap of the secondary shock region and the compensating tensile residual stress area of the material surface adjacent the primary shock region.

8. The method according to claim 6 for improving material properties of a solid material wherein

the spacial energy distribution of the secondary pulse is symmetric.

9. The method according to claim 6 for improving material properties of a solid material wherein

the spacial energy distribution of the secondary pulse is asymmetric.

10. The method according to claim 6 for improving material properties of a solid material wherein

the secondary shock region overlaps at least a portion of the primary shock region.

11. The method according to claim 10 for improving material properties of a solid material wherein

the secondary shock region overlaps the entire periphery of the primary shock region.

12. The method according to claim 11 for improving material properties of a solid material wherein

the secondary shock region overlaps the entire primary shock region.

13. The method according to claim 10 for improving material properties of a solid material wherein

the secondary shock region and the primary shock region are concentric.

14. The method according to claim 10 for improving material properties of a solid material wherein

the primary shock region is generally circular and the secondary shock region is generally annular surrounding the primary shock region.

15. The method according to claim 10 for improving material properties of a solid material comprising

directing to a secondary shock region, including a substantial portion of the periphery of the primary shock region, a plurality of secondary pulses of laser radiation.

16. A method of improving material properties of a solid material comprising

directing to a primary shock region of the surface of the material having a baseline surface residual stress, at least one primary laser pulse having a preselected average energy fluence of at least about 10 J/cm^2 to provide shock waves therein and to thereby induce compressive residual stress in the primary shock region and compensating tensile residual stress in an area of the material surface adjacent the primary shock region, and

shot peening a secondary shock region including at least a portion of the compensating tensile residual stress area of the material surface adjacent the primary shock region such that the compensating tensile residual stress is reduced in the area of overlap of the secondary shock region and the compensating tensile residual stress area of the material surface adjacent the primary shock region.

17. The method according to claim 16 for improving material properties of a solid material comprising

shot peening the secondary shock region such that the compensating tensile residual stress is reduced to below the baseline surface residual stress in the area of overlap of the secondary shock region and the compensating tensile residual stress area of the material surface adjacent the primary shock region.

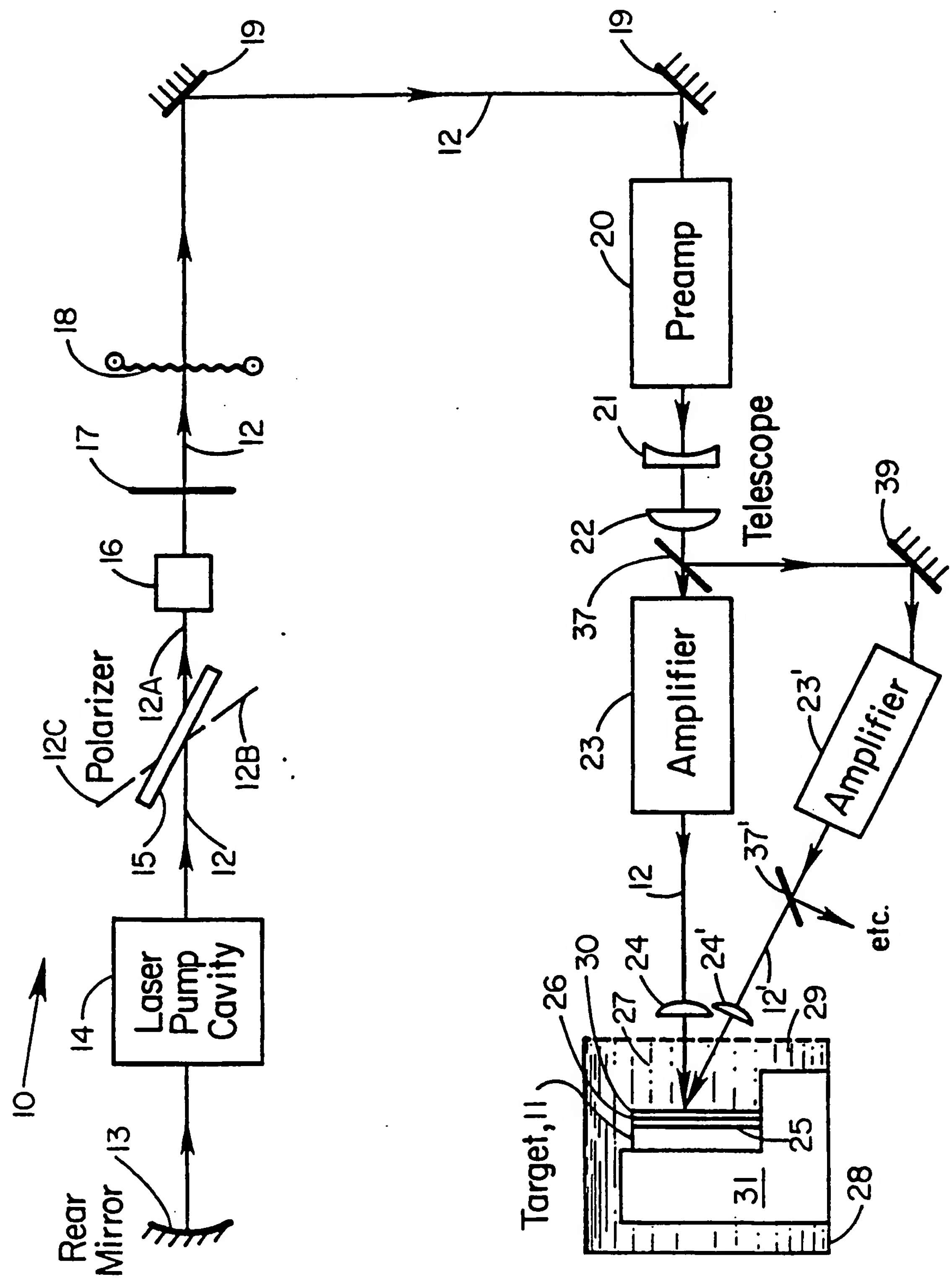

Rear Mirror
13
10
Laser Pump Cavity
14
15
12
12C
Polarizer
12A
12B
16
17
12
18
19
12
19
Preamp
20
21
Telescope
22
37
Amplifier
23
39
Amplifier
23'
37'
etc.
12
12'
24
24'
30
26
27
29
Target, 11
25
31
28

FIG. 1

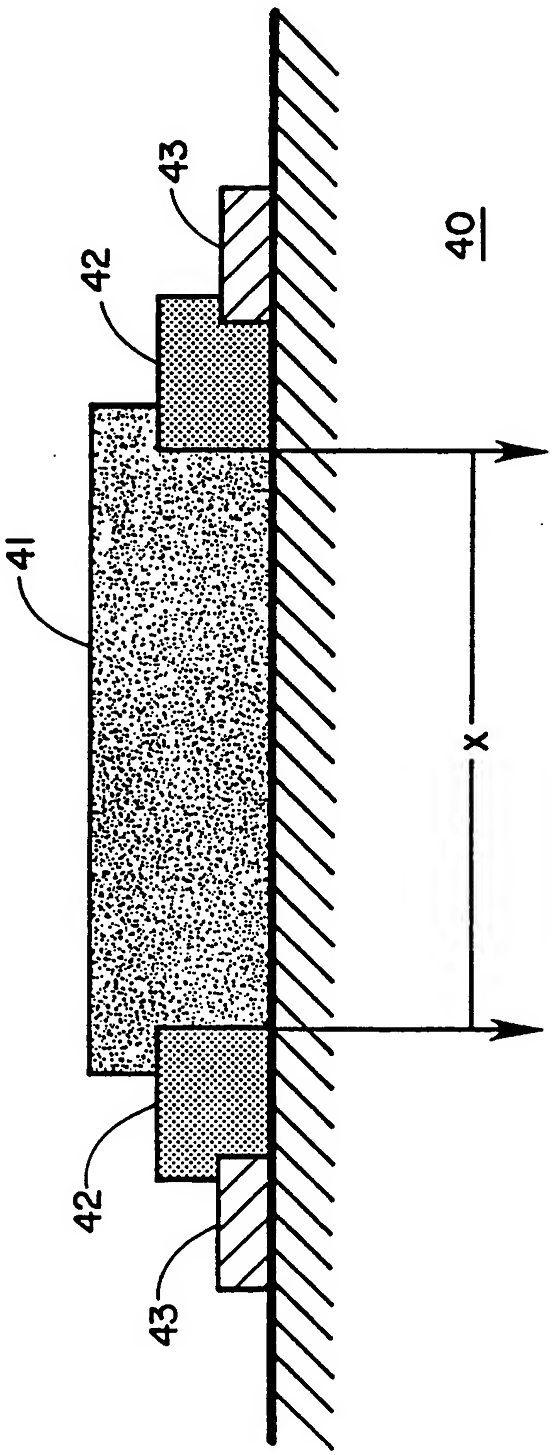


FIG. 2

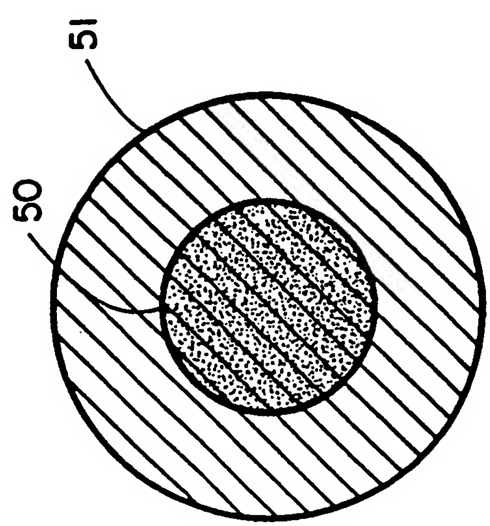


FIG. 3A

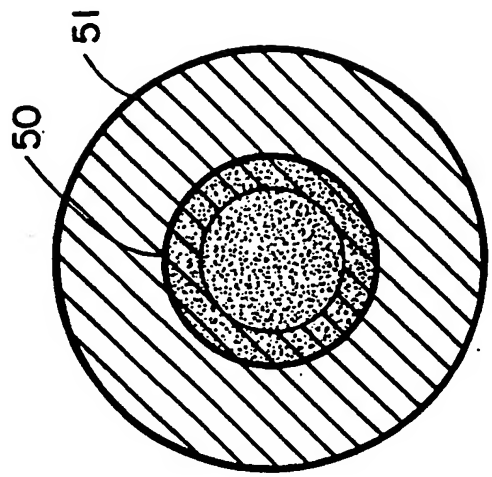


FIG. 3B

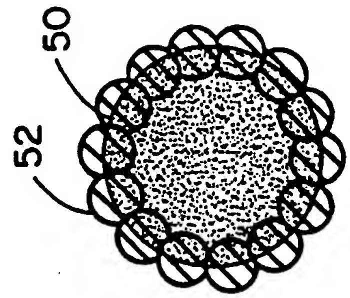


FIG. 3C

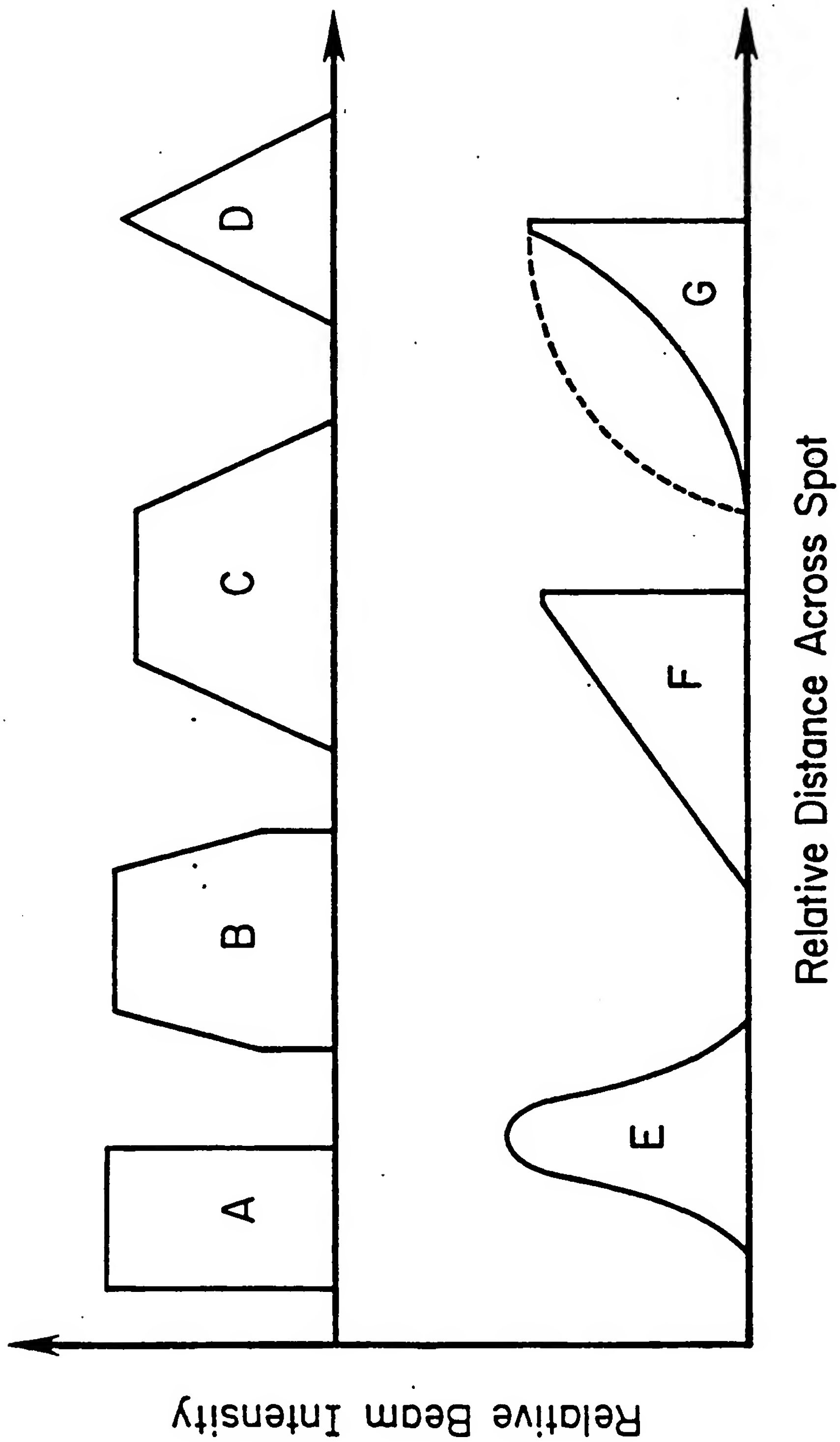

A
B
C
D
E
F
G
Relative Distance Across Spot
Relative Beam Intensity

FIG. 4

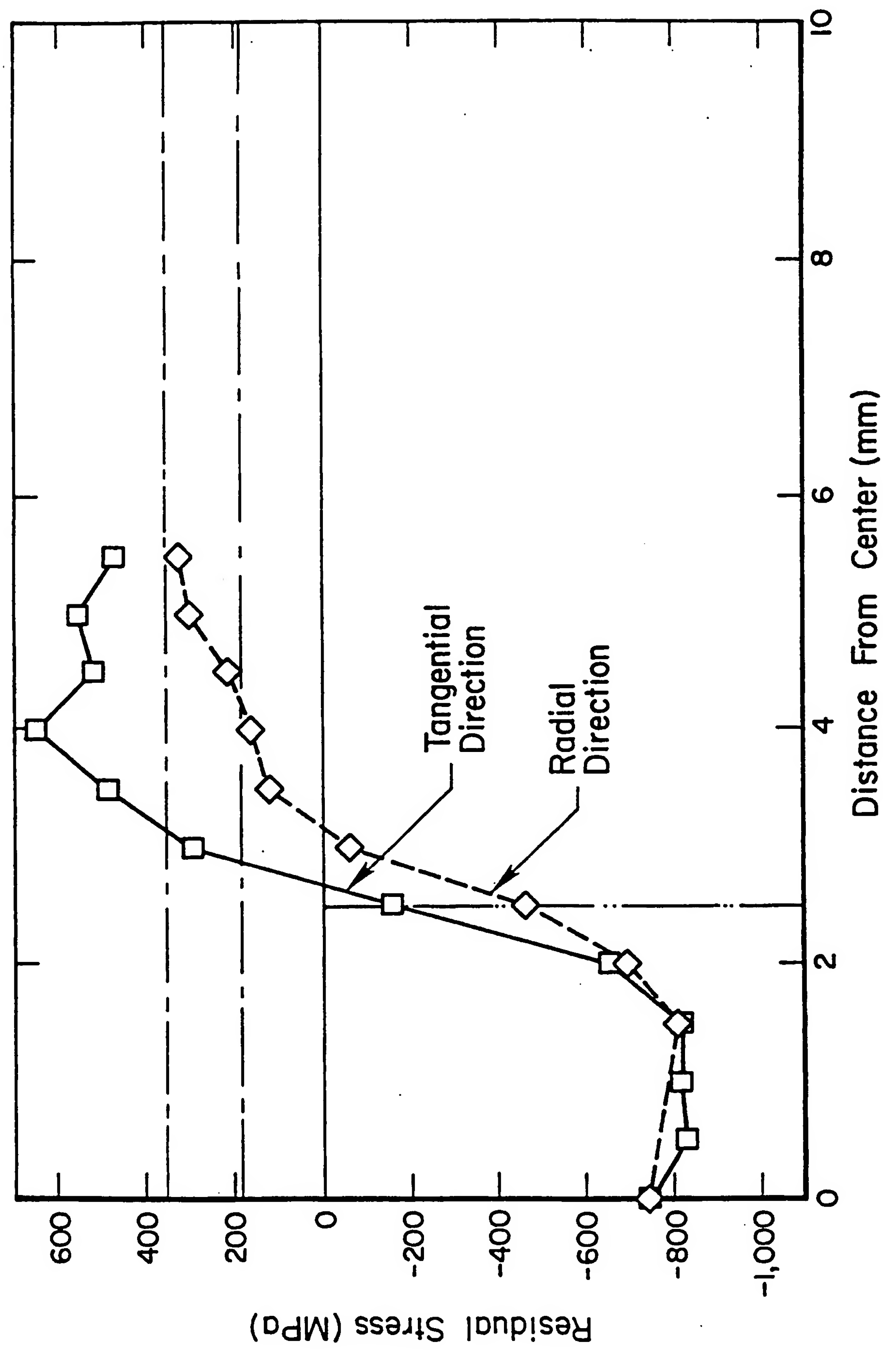
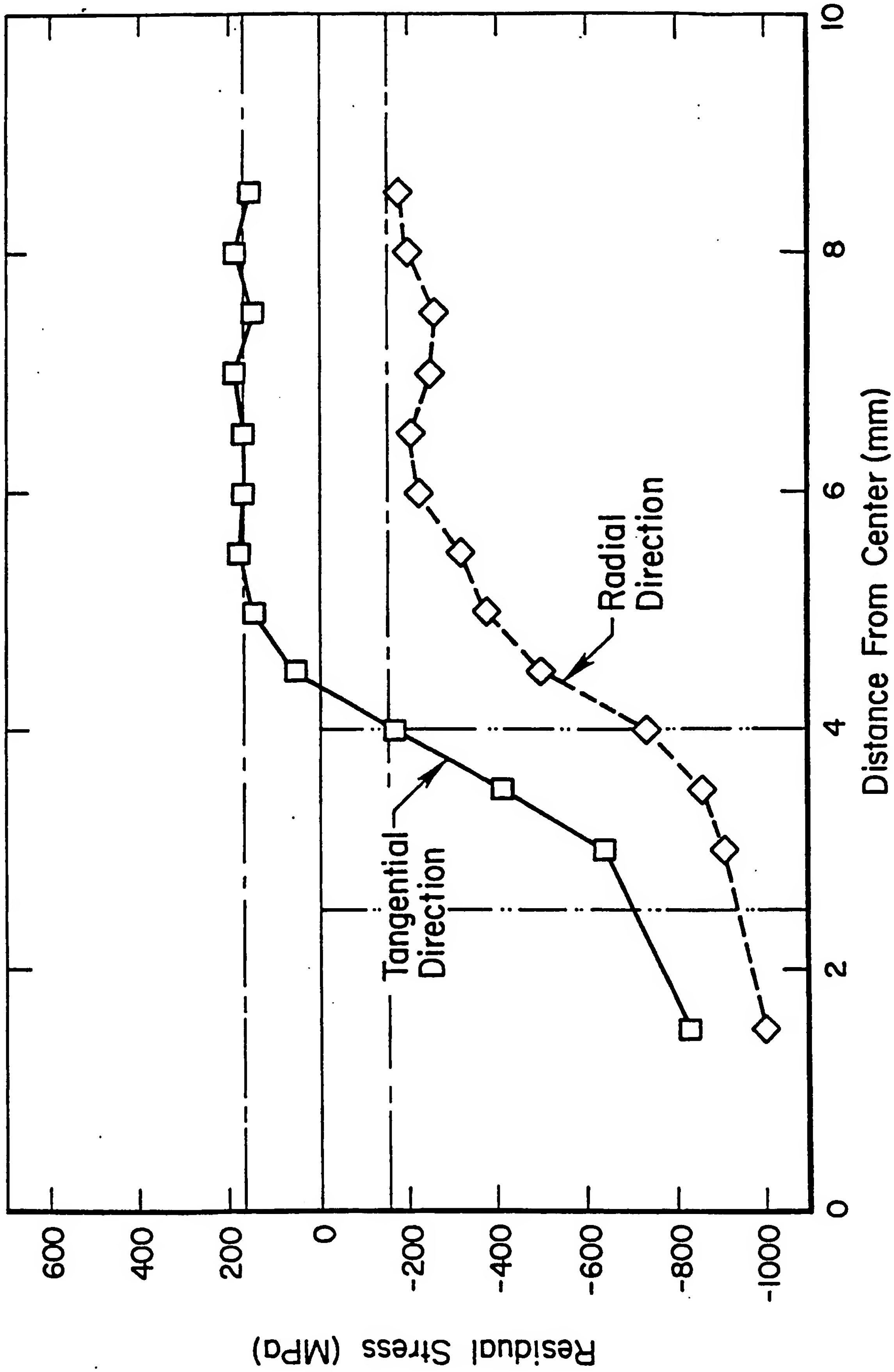

Residual Stress (MPa)
600
400
200
0
-200
-400
-600
-800
-1,000
Distance From Center (mm)
0
2
4
6
8
10
Tangential Direction
Radial Direction

FIG. 5A



600
400
200
0
-200
-400
-600
-800
-1000
Residual Stress (MPa)
0
2
4
6
8
10
Distance From Center (mm)
Tangential Direction
Radial Direction

FIG. 5B

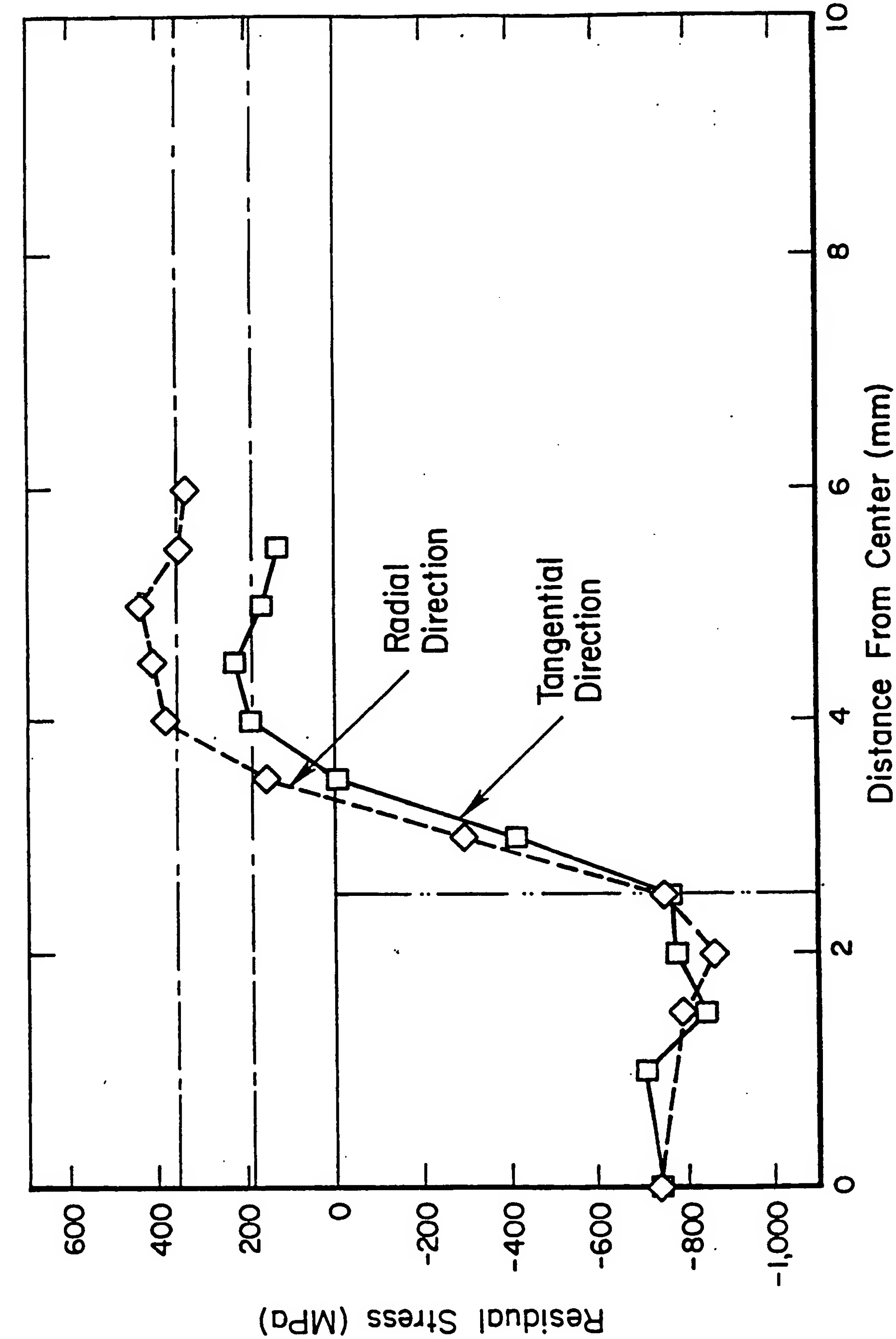

Residual Stress (MPa)
600
400
200
0
-200
-400
-600
-800
-1,000
Distance From Center (mm)
0
2
4
6
8
10
Radial Direction
Tangential Direction

FIG. 6A

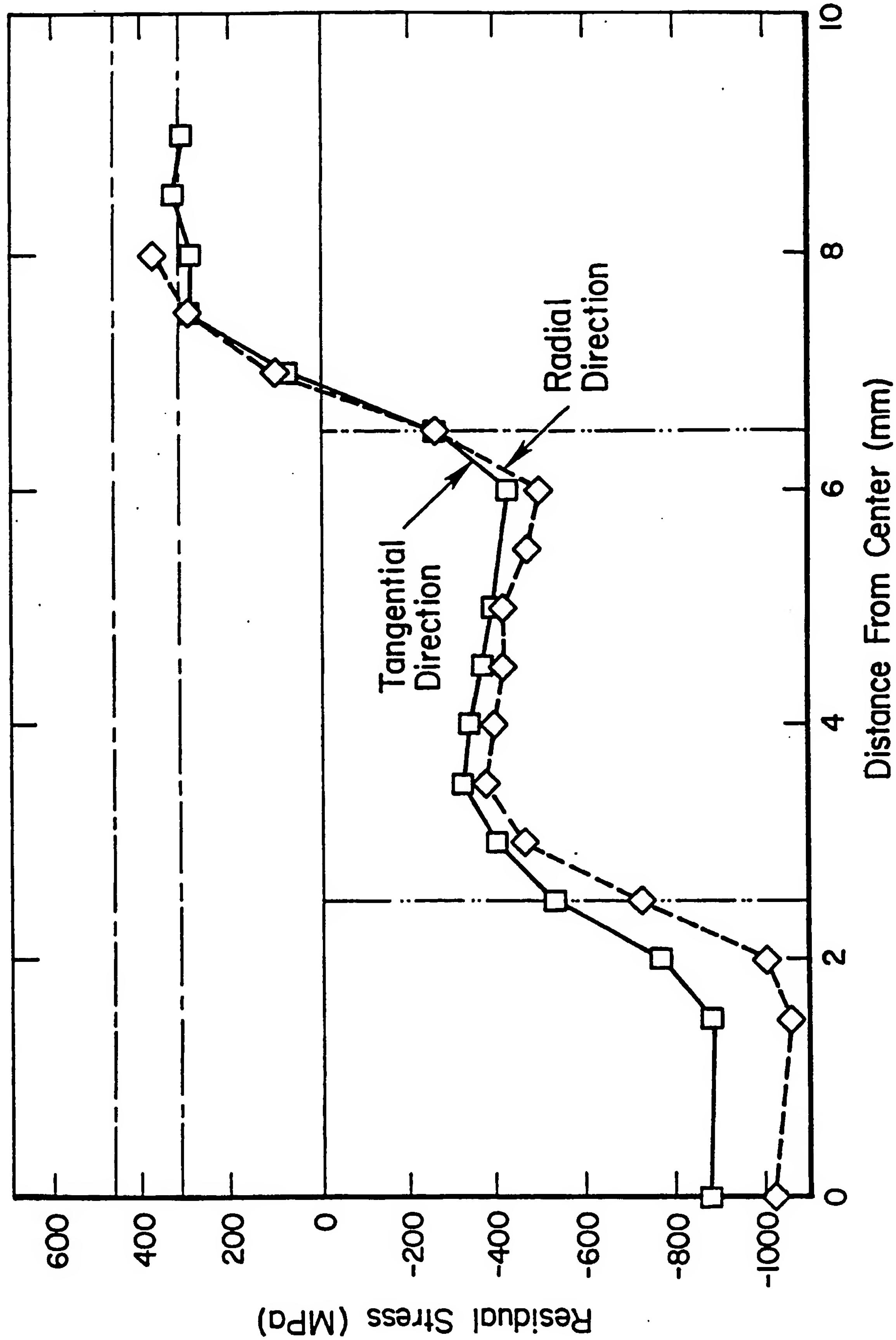

Residual Stress (MPa)
600
400
200
0
-200
-400
-600
-800
-1000
0
2
4
6
8
10
Distance From Center (mm)
Tangential Direction
Radial Direction

FIG. 6B

INTERNATIONAL SEARCH REPORT

Intern. al Application No
PCT/US 95/03532

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 C21D10/00 C21D7/06 C22F3/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 C21D C22F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO-A-91 11538 (BATTELLE MEMORIAL INSTITUTE) 8 August 1991 cited in the application see page 31, paragraph 1 - paragraph 2; claim 1; figures 1,6 ---	1,6,16
A	US-A-3 850 698 (MALLOZZI P ET AL) 26 November 1974 cited in the application see example 1 ---	1,6,16
A	US-A-4 937 421 (ORTIZ JR ANGEL L ET AL) 26 June 1990 see claim 1 ---	1,6,16
	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

3

Date of the actual completion of the international search	Date of mailing of the international search report
19 July 1995	28.07.95

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Gregg, N

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 95/03532

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	PATENT ABSTRACTS OF JAPAN vol. 012 no. 143 (C-492) ,30 April 1988 & JP,A,62 260015 (SUMITOMO ELECTRIC IND LTD) 12 November 1987, see abstract	16,17
A	US,A,4 428 213 (J.W.NEAL ET AL) 31 January 1984 see claim 1	16

3

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
WO-A-9111538	08-08-91	AT-T-	124465	15-07-95
		CA-A-	2072070	12-07-91
		EP-A-	0510124	28-10-92
		JP-T-	5503738	17-06-93
		US-A-	5127019	30-06-92
		US-A-	5131957	21-07-92
US-A-3850698	26-11-74	NONE		
US-A-4937421	26-06-90	NONE		
US-A-4428213	31-01-84	NONE		